1. Background and Summary of Findings

In 1942, the United States of America began to develop technology capable of producing nuclear weapons under the U.S. Army Corps of Engineers' Manhattan Engineer District (known as the Manhattan Project). Initial efforts resulted in the first atomic bombs used at the end of World War II. With the enactment of the Atomic Energy Act of 1946, nuclear weapons development and production was transferred to the newly-created civilian Atomic Energy Commission (AEC). AEC developed and managed a network of research, manufacturing, and testing sites, focusing the efforts of these sites on stockpiling an arsenal of nuclear weapons. Initially, the nuclear weapons production network was small and scattered, relying on many small, privately owned facilities. In the late 1940s and early 1950s, during a period of great expansion of the nuclear weapons complex, most of these functions were consolidated into a complex of large, centralized, government-owned production facilities.

Congress abolished AEC in 1975. Its nuclear weapons production mission was incorporated into the Energy Research and Development Administration (ERDA), which was subsumed into DOE in 1977.

Stockpiling nuclear materials and weapons required an extensive manufacturing effort that generated large volumes of waste and resulted in considerable environmental contamination. Growing concerns about safety and environmental problems caused various parts of the weapons-producing complex to be shut down in the 1980s. These shutdowns, at first expected to be temporary, became permanent when the Soviet Union dissolved in 1991. Although the nation continues to maintain a reduced arsenal of nuclear weapons and a limited production capability, the Department has largely suspended nuclear weapons production activities and begun to downsize the weapons complex as part of the stockpile stewardship and management program. Production materials and facilities once considered vital to national defense have become excess to the Department's current mission needs. The primary missions of many former nuclear weapons production sites are now environmental restoration, waste management, nuclear material and facility stabilization, and technology development.

In 1989, the Secretary of Energy created the Office of Environmental Restoration and Waste Management (later renamed the Office of Environmental Management) to consolidate budgets and staff devoted to similar environmental tasks within the Department into a single DOE program office. The Office of Environmental Management (EM), through the Department's many field and operations offices, is acting to mitigate the risks and hazards posed by the legacy of nuclear weapons production. Essentially all of the identified legacy waste and environmental damage situations have been, or are being, addressed under the provisions of federal and state law, including the Federal Facility Compliance Act and the agreements made pursuant thereto.

Other DOE Reports on the Environmental and Potential Human Health Impacts of Nuclear Weapons Production

- *Closing the Circle on the Splitting of the Atom: The Environmental Legacy of Nuclear Weapons Production and What the Department is Doing About It*, DOE/EM-0266 (1996).
  - Describes the origin and ongoing cleanup of the environmental legacy of nuclear weapons production.
- *Estimating the Cold War Mortgage: The 1995 Baseline Environmental Management Report*, DOE/EM-0232 and 1996 update, DOE/EM-0290.
  - Estimates the life-cycle activities and costs of the DOE Environmental Management Program.
- *Risks and the Risk Debate: Searching for Common Ground*, (1996).
  - Evaluates the risks that the Department's environmental legacy poses to its workers, the public, and the environment.

Surplus facilities. Hanford's B Reactor was the first plutonium-production reactor in the world. Plutonium created in this reactor fueled the first atomic explosion in the Alamogordo desert on July 16, 1945 and it formed the core of the bomb that exploded over Nagasaki on August 9, 1945. Built in less than one year, the B Reactor operated from 1944 until 1968. It has been designated a National Historic Mechanical Engineering Landmark. *100-B Reactor Area, Hanford Site, Washington. July 11, 1994.*

Although the Department is committed to long-term cleanup of the nuclear weapons complex, it is not possible to return all contaminated DOE sites to unrestricted public use. Nuclear material and facility stabilization, remediation, and waste management will be supplemented with monitoring, land-use restrictions, and other institutional controls to protect human health and safety over the long term.

THE FOUR ELEMENTS OF THE ENVIRONMENTAL LEGACY

Section 3154 of the National Defense Authorization Act for Fiscal Year 1995 directs the Department to describe each step of the complete cycle of production and disposition of nuclear weapons components by the Department of Energy of all waste streams generated before 1992 (See Appendix D). The goal of *Linking Legacies* is to provide Congress with as comprehensive and accurate a picture as possible of the environmental results of each step of the weapons production and disposition cycle. The report broadly applies the term "waste streams" to include four major legacy elements:

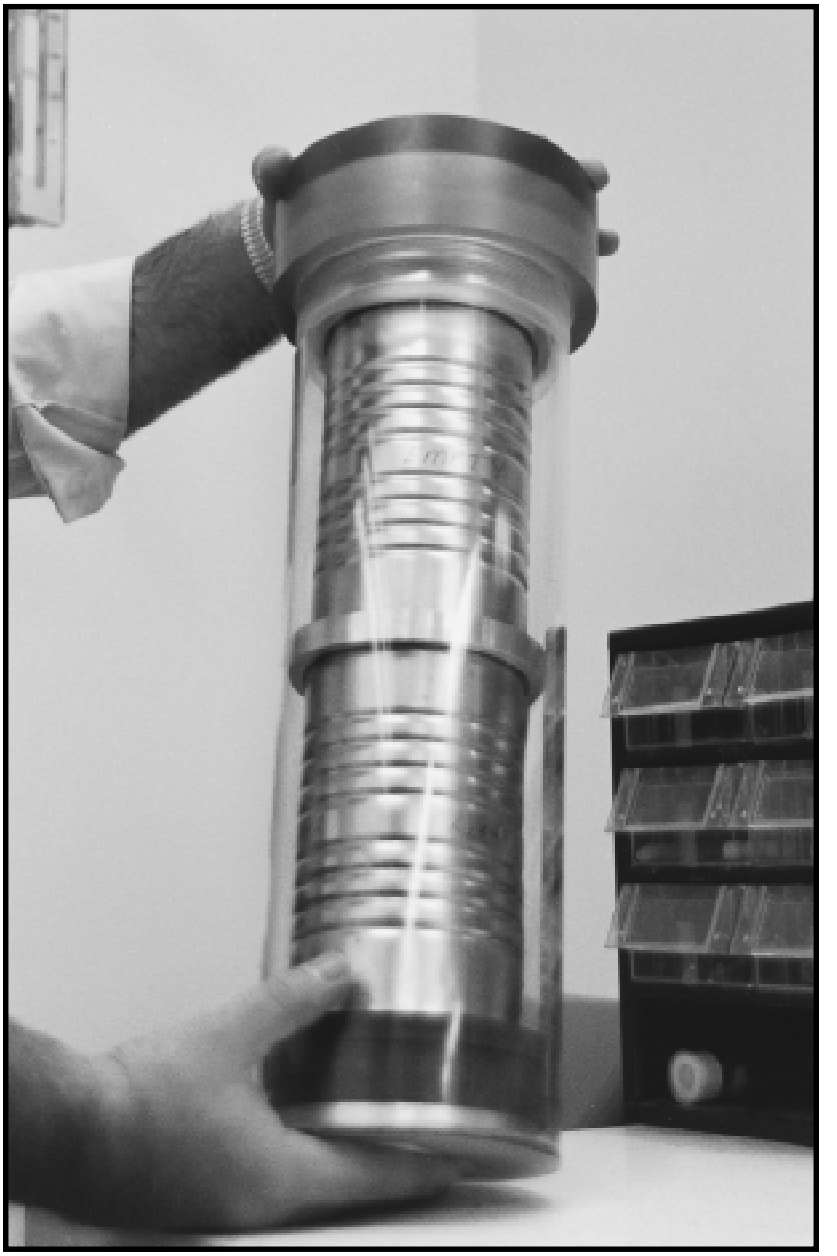
- **Waste**, including high-level, transuranic, low-level, and hazardous waste, byproduct material as defined under Section 11e(2) of the Atomic Energy Act of 1954, as amended, and other waste;
- **Contaminated environmental media**, which include soils, groundwater, surface water, sediments, debris, and other materials;
- **Surplus facilities** once used for nuclear weapons production that are no longer needed and are slated to be deactivated and decommissioned; and
- **Materials in Inventory**, which includes all materials not used in the past year and not expected to be used in the upcoming year.

Detailed reports on each element are found in Chapters 3 through 6.

This report analyzes the origins of the Department's current waste inventories. It does not document or recreate historical waste generation, management practices, or releases.

Contaminated environmental media are included in this report because many waste streams were managed in a manner that resulted in releases to the environment. Surplus facilities and materials in inventory are also included because, like waste and contaminated media, they require long-term management even if they are not technically considered "waste."

The Department suspended much of its nuclear weapons production activities prior to 1992. Since that time, a large number of potential release sites, wastes, and facilities have been characterized, and many waste management and cleanup activities have been completed. The data in this report reflect the status of the environmental legacy of the nuclear weapons complex as of mid-1996.



Materials in Inventory. Plutonium is one of the most challenging of the Department of Energy's ten categories of Materials in Inventory. The steel cans shown here have been approved by the U.S. Department of Transportation for shipping plutonium oxide powder and metal across the nation. They are the same kinds of containers used in the commercial food industry. *DOE ZR inner shipping component of a DOT 6M shipping container. Plutonium Finishing Plant, Hanford Site, Washington. December 16, 1993.*

WHAT IS NOT COVERED IN THIS REPORT

The following subjects are not discussed in this report because they either fall outside the scope of the congressional mandate, are unidentifiable and unquantifiable, or are not under the purview of the Department of Energy:

- Wastewater outfalls, stack emissions, and other releases not in identifiable or quantifiable contaminated environmental media;
- Contaminated facilities in use, including active waste management facilities;[1]

[1] *Although individual facilities that remain in use are excluded, sites at which those facilities are located are included if they contain other legacy elements.*

Complexities of the legacy. This facility at the Oak Ridge National Laboratory blended transuranic and low-level radioactive waste with concrete grout, which it then injected into rock fissures deep underground. This technique is termed "hydrofracture," and it was a standard practice at Oak Ridge for 30 years until it was discontinued in 1983. The Department of Energy plans to install a system to detect and monitor contaminants migrating from the grout into surrounding groundwater, although nothing can be done to remove the radioactive grout itself. One of the Department's surplus facilities, the Old Hydrofracture Facility will be dismantled and its injection wells plugged. The process of dismantlement will generate radioactive waste, but the radioactive scrap metal may be recycled. The large rust spots visible in the photo are the result of hammer blows delivered decades ago to dislodge drying concrete from inside the tank walls. *Old Hydrofracture Facility, Melton Valley, Oak Ridge Reservation, Oak Ridge, Tennessee. January 10, 1994.*

- Materials in use or in strategic reserves;
- Nonradioactive hazardous waste disposed of at commercial facilities;[2]
- Nonhazardous, nontoxic, and nonradioactive waste, e.g., sanitary waste that does not require special management;
- Waste, environmental contamination, surplus facilities, and superfluous materials from the military deployment of nuclear weapons, such as surplus missile silos and contaminated groundwater at bases for strategic bombers;
- Waste, environmental contamination, surplus facilities, and superfluous materials managed by the commercial nuclear industry, (e.g., spent nuclear fuel from nuclear power plants and commercial low-level waste disposal facilities);
- Risk and cost implications of the environmental legacy of nuclear weapons production; and
- Social, economic, and political legacies of nuclear weapons production and the Cold War.

[2] *These materials are presumed to have been treated, stored, and disposed of in a manner that obviates the need for continued management. Any environmental impacts of treatment, storage, and disposal services paid for by DOE would be indistinguishable from the impacts of the management of non-DOE wastes. However, in several cases DOE is a potentially responsible party for hazardous waste sites listed on the EPA National Priorities List, under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), commonly known as Superfund.*

Contaminated environmental media. From 1944 until 1957, untreated liquid low-level radioactive waste from the Oak Ridge National Laboratory was discharged into White Oak Creek, which then flowed directly into the Clinch River. Today, the waters of White Oak Creek carry sediments contaminated with strontium-90, tritium, cesium-137, cobalt-60, and PCBs. These contaminants come from past laboratory discharges and waste storage area seepages. To insure that most of the contaminated particles settle out of the creek water before it flows into the Clinch River, the Department of Energy has constructed a state-of-the-art embayment dam, and, above it, White Oak Lake (pictured here). *White Oak Lake, one mile from Oak Ridge National Laboratory, Oak Ridge, Tennessee. January 11, 1994.*

PROCESSES THAT GENERATED THE LEGACY OF NUCLEAR WEAPONS PRODUCTION

This report describes nuclear weapons production activities in terms of eight general groupings of manufacturing processes; a description of each is essential to gain an understanding of the analyses in this report. The eight general groupings of activities are:

- Uranium Mining, Milling, and Refining
- Isotope Separation (Enrichment)
- Fuel and Target Fabrication
- Reactor Operations
- Chemical Separations
- Weapons Component Fabrication
- Weapons Operations
- Research, Development, and Testing

A brief description of each of these processes is contained in Chapter 2. A more detailed discussion of the processes can be found in Appendix B.

Nonweapons activities also took place at the DOE weapons complex sites. These activities generated waste and contaminated media similar in character and quantity to those resulting from nuclear weapons production. Nonweapons activities are grouped into the following two categories in this report:

- **Support for the Naval Nuclear Propulsion Program.** The Naval Nuclear Propulsion Program is a joint DOE and U.S. Navy program responsible for the design, testing, construction, and operation of nuclear propulsion systems for surface warships and submarines. The Department produced highly-enriched uranium for the Navy at its nuclear weapons complex facilities. DOE continues to accept spent nuclear fuel from Naval nuclear reactors. From 1952 until 1992, Naval reactor fuel was processed to recover enriched uranium for reuse in the weapons programs.
- **Non-defense Research and Development.** A wide variety of non-defense programs have been administered by DOE and its predecessor agencies. Since the beginning of the "Atoms for Peace" program in 1954, the federal agencies charged with administering and regulating the production and uses of atomic power have supported research and development of civilian uses of nuclear energy. These agencies have led the effort to develop nuclear power plants, supplied enriched uranium to civilian reactors, and constructed and operated prototypes and demonstration plants. The Department and its predecessor agencies have also managed many research programs addressing energy supply and basic and applied science and technology.

SUMMARY OF FINDINGS

The major findings about the origins and characteristics of each element of the environmental legacy are summarized here. Chapters 3 through 6 present detailed results and conclusions for each element.

This report summarizes the volumes, locations, and radioactivity (where applicable) for each of the four legacy elements. Other measures that assist in explaining the size and scope of the legacy are included. This report quantifies the portion of each legacy element that resulted from nuclear weapons programs, and it allocates the nuclear weapons-related portion of each legacy element among the eight weapons production process steps.

The data in this report support several general conclusions:

The largest portion of the environmental legacy of nuclear weapons production resulted from the production of plutonium and highly-enriched uranium. Assembly of weapons from these fissile materials added relatively little. Fissile materials production encompasses uranium mining, milling, and refining, uranium enrichment, fuel and target fabrication, reactor operations, and chemical separations processes. Fissile materials production for nuclear weapons has been discontinued.

One operation accounted for more waste and contamination than any of the other seven steps in the nuclear weapons production process: chemical separations, which involves dissolving spent nuclear fuel rods and targets in acid and separating out the plutonium and uranium using a chemical process. Waste generated by chemical separations processes accounted for more than 85 percent of the radioactivity generated in the nuclear weapons production process. In addition, chemical separations generated 71 percent of the contaminated water and 33 percent of the contaminated solids (soil, rubble, debris, sludge, etc.). Finally, 24 percent of the contaminated surplus facilities for which the Department is responsible were attributed to chemical separation operations.

These environmental concerns, which have now been quantified in this report, are among the reasons the Department has begun developing alternatives to traditional chemical separations technologies to stabilize spent fuel and targets for long-term safe storage and permanent disposal. Initial results indicate that substantial safety and cost benefits can result from using these alternative technologies. Making this information available and acting on it can help to stabilize irradiated materials, thereby improving nuclear safety, saving money, and promoting nuclear nonproliferation.

The scope of the DOE Environmental Management program is mostly attributed to the nuclear weapons programs of the Department and its predecessor agencies. Weapons production attributed for 68 percent of the waste volume and 89 percent of the waste radioactivity. Also, 81 percent of the volume of contaminated media and 76 percent of the surplus facilities legacy resulted from weapons-related activities. By mass, 49

Major Findings

Waste (Chapter 3):

Waste Type Data 380,000 cubic meters (100 million gallons) of high-level waste, 220,000 cubic meters (50 million gallons) of transuranic waste, 3.3 million cubic meters (870 million gallons) of low-level waste, 32 million cubic meters (8.5 billion gallons) of 11e(2) byproduct material, 146,000 cubic meters (38.5 million gallons) of mixed low-level waste, and 79,000 cubic meters (28 million gallons) of other waste.

- 68 percent of waste by volume is from weapons production.
- 89 percent of waste radioactivity is from weapons production, 11 percent is from nonweapons programs.
- 89 percent of waste by volume is 11e(2) byproduct material from uranium mining, milling, and refining.
- 94 percent of waste radioactivity is in high-level waste from nuclear weapons and nonweapons chemical separation.

Contaminated Environmental Media (Chapter 4):

Contaminated Solid Media 79 million cubic meters (21 billion gallons).

- 95 percent of contaminated solid media is soil.
- 70 percent of contaminated solid media is contaminated with radionuclides, 14 percent with hazardous substances, 16 percent both.
- 93 percent of contaminated solid media by volume is from nuclear weapons production.
- 32 percent of solid media contamination is associated with chemical separation for nuclear weapons production; 37 percent with research, development, and testing nuclear weapons; 11 percent with fuel and target fabrication from nuclear weapons production; and 20 percent with other DOE activities.

Contaminated Water 1,800 million cubic meters (475 billion gallons).

- More than 99 percent of contaminated water is groundwater.
- 14 percent of contaminated water is contaminated with hazardous constituents, 57 percent by radionuclides, 29 percent both.
- 81 percent of contaminated water by volume is from nuclear weapons production.
- 70 percent of water contamination is associated with chemical separation for nuclear weapons production, 19 percent with various nonweapons activities, and 11 percent with other DOE activities.

Surplus Facilities (Chapter 5):

Number of Facilities Approximately 5,100 facilities.

- 76 percent of facilities are weapons-related.

Materials in Inventory (Chapter 6):

Total Mass 820 million kilograms (1,800 million pounds).

- 49 percent of materials in inventory by mass is from weapons production.
- 71 percent of materials in inventory by mass is depleted uranium and 19 percent is scrap metal.
- Enrichment for weapons production produced 38 percent of the material by mass, and enrichment also produced much of the nonweapons material, including much of the depleted uranium, scrap metal, and lithium.

percent of the Department's materials in inventory were procured for, used in, or created by, nuclear weapons programs. The balance of the legacy waste, contamination, materials, and facilities is largely attributable to nuclear energy or energy research programs.

The distinction between the legacy of nuclear weapons and other U.S. government nuclear activities is not always clear. For example:

- The same mines and mills that provided uranium to AEC for nuclear weapons production also provided uranium to AEC for nonweapons programs, including use in naval propulsion reactors, research and test facilities, and commercial power plants.

Methodology

ESTABLISH FRAMEWORK

- Identify universe of legacy materials
- Define eight weapons production process categories:
  - Uranium Mining, Milling, and Refining
  - Isotope Separation (Enrichment)
  - Fuel and Target Fabrication
  - Reactor Operations
  - Chemical Separations
  - Weapons Component Fabrication
  - Weapons Operations
  - Research, Development, and Testing
- Define the four legacy elements:
  - Waste
  - Contaminated Media
  - Surplus Facilities
  - Materials in Inventory
- Peer Review of Analytical Framework

GATHER DATA

- Identify sources of data for each legacy element
- Compile data on historic site missions

ASSIGN MATERIALS TO THE FOUR LEGACY ELEMENTS

- Compare data between sources
- Identify double-counted and unquantified materials
- Eliminate excluded materials

ATTRIBUTE MATERIALS TO WEAPONS AND NONWEAPONS CATEGORIES IN PRODUCTION PROCESSES

- Initial assignment based on site of origin
- Investigate historical operations conducted at sites
- Identify data gaps and develop assumptions
- Revise assignments as necessary based on information about specific historical operations and assumptions

• After 1964, uranium enrichment in the United States was increasingly devoted to naval propulsion reactors, research and test facilities, and commercial nuclear power plants, even though it took place in the same plants that had produced enriched uranium for nuclear weapons. Furthermore, enriched uranium from nonweapons programs was often recycled back to nuclear weapons programs, and enriched uranium produced for the weapons programs was reused in nonweapons programs.

• Nuclear reactors and chemical separation plants constructed and operated primarily to support nuclear weapons production have also produced nuclear materials for nonweapons programs.

METHODOLOGY

To prepare this report, the Department gathered the latest data available for each of the four legacy elements (waste, contaminated environmental media, surplus facilities, and materials in inventory). The data were analyzed to categorize each element of the legacy according to the nuclear weapons process or nonweapons activity from which it resulted. This methodology required assumptions and expert judgment where specific data were not available.

A summary of the methodology used to prepare this report is shown in the text box "Methodology." More detailed information about the methodology used to measure and categorize each legacy element is found in Chapters 3 through 6.

DATA SOURCES AND LIMITATIONS

Most of the data sources used for this report contain information compiled for reasons different from those underlying this report. As a result, some judgments were necessary in interpreting and adapting the existing information to satisfy the requirements of Section 3154 of the National Defense Authorization Act for Fiscal Year 1995.

Specific issues concerning the data for each legacy element are discussed in detail in Chapters 3 through 6. The quantities of waste, contaminated environmental media, surplus facilities, and materials in inventory attributed to the weapons programs and to particular processes are not precise. However, they represent the Department's best judgment based on available data.

While this report covers all four legacy elements in an effort to respond fully to the congressional request, the Department is not able to provide the same level of detail for contaminated environmental media, surplus facilities, and materials in inventory as it does for waste. It was possible to present a detailed

Waste. A painted plastic owl deters birds and mice from nesting among drums of transuranic waste inside a storage dome at the Los Alamos National Laboratory. The drums contain waste contaminated with plutonium and other long-lived radioactive heavy elements. Nuclear weapons research, design, and development generated most waste stored here. *Transuranic Waste Storage Dome, Building 48 East, Technical Area 54, Area G, Los Alamos National Laboratory, New Mexico. February 24, 1994.*

description of volumes, locations, radionuclide content, and hazardous constituents for most waste because mature data are readily available. Data in this report for the other elements are not as complete. Key issues for each legacy element include:

- *Waste* – The Department can provide a reasonably accurate inventory of its waste volumes and characteristics. However, changes between 1942 and 1992 in the definitions of waste categories have caused uncertainty in the categorization of some waste.
- *Contaminated Environmental Media* – Characterization of some potential release sites is not yet complete. The Department is engaged in a multi-year effort to characterize these remaining sites. Additionally, there are different ways to define and quantify contaminated environmental media.
- *Surplus Facilities* – Counting the number of surplus facilities provides only a limited understanding of this element. Size, extent of contamination, condition, type of construction, and other factors vary considerably among the Department's surplus facilities. Some facilities had multiple uses, with each activity responsible for a portion of contamination. With limited information on hand, some judgment was required to attribute certain facilities to the weapons program or to specific processes. Finally, the number of surplus facilities will change in the future when the Department declares additional facilities to be surplus, and as surplus facilities are decommissioned.
- *Materials in Inventory* – The Department began only in the last year to quantify and characterize its materials in inventory. Although the Department has obtained comprehensive, centralized inventory information on ten categories of materials in inventory through the Materials in Inventory Initiative, there are many additional materials at Department-owned facilities that have not been examined.